10/530270
JC06 Rec'd PCT/PTO 05 APR 2005

APPARATUS AND METHOD FOR TRANSMITTING A SIGNAL FROM DEEP IN A WELLBORE THROUGH A STRING OF TUBULARS

The present invention relates to an apparatus for transmitting a signal from deep in a wellbore through a string of tubulars. The invention particularly, but not exclusively, relates to a method and apparatus for transmitting communication data from deep in a wellbore through a string of tubulars, such as a tool string or a string of drill pipe to the surface during the exploration, construction and production phases.

The transmission of data through a drill string has been performed by several methods in the past. The first of these was through the use of a wire line dropped through the inside of the drill pipe. This wire line would include a mechanical cable for placement and retrieval of the sensors or controls as well as a protected data pathway such as a wire or a fibre optic cable. The expense of this system along with the problems caused by damage to either the line or the pipe and the pressure loss caused by this system led to the development of other systems using communications methods including the transmission of acoustic pulses caused by pressure changes in the drilling fluids or the acoustic transmission of the data to the surface. The primary limitation of acoustic or pressure methods in the transfer of data has been the very low data transfer rate, in the order of a few bits per second. Further attempts have been made in accomplishing the data transfer by the use of loose wire or fibre optic cables within the pipe, but none of these systems has proven to be reliable.

U.S. Patent Application Publication No. 2002/0075114

entitled "A Data Transmission System for A String of Downhole Components", by Hall et al., teaches a system for transmitting data through a string of downhole components. In accordance with one aspect of the invention, the system includes a plurality of downhole components, such as sections of pipe in a drill string. Each downhole component includes a pin end and a box end, with the pin end of one downhole component being adapted to be connected to the box end of an other. Each pin end includes external threads and an internal pin face distal to the external threads. Each box end includes an internal shoulder face with internal threads distal to the internal shoulder face. The internal pin face and the internal shoulder face are aligned with and proximate each other when the pin end of the one component is threaded into a box end of the other component. The system also includes a first communication element located within a first recess formed in each internal pin face and a second communication element located within a second recess formed in each internal shoulder face. The first and second communication elements are inductive coils. The inductive coils each lie within a magnetically conductive, electrically insulating element, which take the form of a U-shaped trough. The system also includes a conductor in communication with and running between each first and second communication element in each component. The data transmission system of the Hall patent, however, is difficult and expensive to manufacture. The Hall system cannot be easily retrofitted into existing drill pipe. If there is a failure in one section of pipe or in a communication element between adjacent pipes, all data communication is lost.

The typical environment in which these downhole communication systems are used requires that they be able to withstand temperatures above 400 degrees Fahrenheit and the turbulent flow of drilling fluids through the pipe along with possible mechanical damage caused by devices inserted through the pipe. Thus there is a need for a reliable and durable communication method and apparatus for transferring data at a high speed along a drill pipe during operations down hole in a well bore. Thus, there is a need for a downhole communication path that is easy to manufacture and retrofit into existing drill pipe.

In the prior art, transmission of signals from deep in a well bore was carried out through wires on a wire lines or wires wholly enclosed and encased in the wall of the tubular, as disclosed in U.S. Patent Application, publication under number 2002/0075114.

In accordance with the present invention, there is provided an apparatus for transmitting a signal from deep in a wellbore through a string of tubulars the apparatus comprising an signal conductor and a tubular characterised in that the signal conductor is located adjacent an interior surface of the tubular. Preferably, the signal conductor is fixed in relation to the interior surface of the tubular.

Preferably, the signal conductor is an electrical conductor. Most logging tools and downhole data acquisition tools produce an electric signal. It is preferred to retain the signal in electrical form. Advantageously, the electrical conductor is isolated from the interior surface of the tubular by a layer of electrically insulative material. The insulative material

may be a plastics material which is applied to the electrical conductor or preferably, the interior surface of the tubular is coated in the insulative layer. Advantageously, the insulative layer adheres itself to the interior wall of the tubular.

Advantageously, the electrical conductor is a wire. The wire is preferably of round cross-section or most preferably of rectangular cross-section, such that the cross sectional area of the electrical conductor is sufficient to carry the signal along a predetermined length with an acceptable line loss and to minimise impingement on the free internal diameter of the tubular. It is important that tools, darts, bombs, plugs, wire line tools, logging tools and any other objects or instruments etc will not get stuck by a reduced diameter bore in the tubular and also so that flow of mud will not be affected. Preferably, the wire is embedded in a protective layer. A thin layer over the top of the wire preferably coats the conductor and provides a electrically insulative layer and gives some damage protection.

Alternatively or preferably, the electrical conductor is a piece of foil. The piece or sheet of foil may be a single sheet lining the entire surface of the interior wall of the tubular. However, it is preferred that the sheet of foil is split into a plurality, preferably four strips separated by an electrically insulative gap or protective layer. Advantageously, a protective layer covers the sheet of foil.

Preferably, the electrical conductor comprises a micro strip line. Advantageously, the micro strip comprises a conductive core and an insulating layer encasing the

conductive core. Preferably, the core is in the form of a rectangular section strip. Advantageously, the core is between 0.048mm (0.0019") and 0.05mm (0.002") thick. The width of the core may be in the order of 1mm. Preferably, the micro strip line has an overall thickness of less than 1mm and preferably less than 0.65mm, so that it does not significantly impinge on the bore of the tubular. Advantageously, the insulating layer is encased in an outer conductive layer, preferably to form a coaxial conductive path. Advantageously, the outer conductive layer is earthed, which preferably reduces interference and reduces line losses by acting as an electrical shield.

Preferably, the signal conductor extends substantially the entire length of the tubular. Advantageously, the tubular comprises a plurality of signal conductors. Preferably, to provide redundancy by passing the same signal through each cable or to increase the bandwidth of the apparatus. Preferably, one of the plurality of signal conductors carries the signal and another of the signal conductors carries substantially the same signal.

Advantageously, the signal conductor is provided with means for transferring the signal from the signal conductor to another signal conductor in an adjacent tubular. The means may comprise a coupling. The coupling may be a conductive coupling, an inductive coupling, an acoustic coupling, or a digital repeater may be used. Preferably, the signal conductor is provided with an antenna at at least one end of the tubular, to transmit or receive the signal from an adjacent tubular or an amplifier-receiver. Preferably, a receiving antenna is

provided at one end of the tubular and a transmitting antenna is provided at the other end of the tubular, the signal conductor arranged therebetween. Advantageously, the antenna comprises the electrical conductor following the interior perimeter of the tubular.

Preferably, the apparatus further comprises an amplifier-receiver. The amplifier-receiver may be place at the end of every tubular. Preferably, at one end of every drill pipe, but alternatively at the end of every stand of drill pipe. Preferably, the transmission apparatus is the transmission apparatus as set out in the following statements and the amplifier receiver is of the type set out in those statements.

The signal conductor may be arranged in a recess in the interior wall of the tubular.

Preferably, tubular is drill pipe. Drill pipe of the type used in drilling and in tool strings.

The present invention also provides a method for transmitting a signal from deep in a wellbore through a string of tubulars, the method comprising the steps of passing the signal through an electrical conductor located adjacent an interior surface of the tubular. Preferably, the method for manufacturing a drill pipe, the method comprising the steps of positioning and fixing an electrical conductor adjacent an interior surface of a drill pipe section.

The present invention also provides a transmission apparatus for transmitting a signal from deep in a wellbore through a string of tubulars, the apparatus comprising an electrical conductor arranged in a tubular characterised in that the apparatus further comprises an amplifier-repeater. The electrical conductor could be

wholly within the wall of the tubular, in a recess in the interior wall of the tubular or wholly on the inner surface of the tubular.

Preferably, the amplifier-repeater comprises a signal amplifier and a power source. Advantageously, the power source comprises a piezoelectric device. The electric charge is obtained from vibration in the tubular caused by flow of mud, action of a mud motor and/or by a drill bit on the end of a pipe string. It is also within the scope of this invention use this effect to create electrical charge by any other means. Alternatively or preferably, the power source comprises a battery. The battery or a capacitor may be rechargeable and may have a piezoelectric device charging the battery or capacitor.

Preferably, the transmission apparatus further comprises a receiver antenna. Preferably, for receiving an RF/induced signal from an antenna hard wired to the end of an electrical conductor in an adjacent tubular, the received signal is then amplified by the amplifier-receiver.

Advantageously, the electrical conductor comprises a transmitter antenna. Preferably, the transmitter antenna may simply be a length of the conductor arranged in close, preferably parallel proximity to a corresponding receiver antenna, which may be a similar length of conductor which preferably has similar impedance characteristics.

Advantageously, the apparatus further comprises a transmitter antenna. Preferably, for transmitting an the amplified signal by RF/induction to an antenna hard wired on the end of an adjacent tubular.

Preferably, the electrical conductor comprises a

receiver antenna. Preferably, the receiver antenna may simply be a length of the conductor arranged in close, preferably parallel proximity to a corresponding transmitter antenna, which may be of a similar length of conductor which preferably has similar impedance characteristics.

Advantageously, the transmission apparatus further comprises a second electrical conductor and a second amplifier-repeater, which may be used to carry the same signal, or a additional signal. Preferably, the transmission apparatus further comprises communication means between the first and second amplifier repeaters. Preferably such that, if one line is cut, both amplifiers can transmit the signal through the next tubular or if one of the amplifier repeaters fails, the signal from the one is automatically forwarded to the other amplifier-repeater for transmission through the next tubular.

Preferably, the transmission apparatus further comprises a third electrical conductor and a third amplifier-repeater. Preferably, for carrying the same signal, or advantageously a second signal. Advantageously, the transmission apparatus further comprises communication means between the first, second and third amplifier repeaters. Preferably such that, if one or two lines is cut, all three amplifiers can transmit the signal through the next tubular or if one or two of the amplifier repeaters fails, the signal from the one is automatically forwarded to the other amplifier-repeater for transmission through the next tubular.

Advantageously, the transmission apparatus further comprises a fourth electrical conductor and a fourth amplifier-repeater. Preferably, for carrying the same

signal, or advantageously the second signal.

Preferably, the transmission apparatus a further comprises communication means between the first, second, third and fourth amplifier repeaters. Preferably, such that, if one, two or three lines are cut, all four amplifiers can transmit the signal through the next tubular or if one, two or three of the amplifier repeaters fails, the signal from the one working amplifier repeater is automatically forwarded to the other amplifier-repeaters in the next tubular.

Advantageously, the amplifier repeater is located in a ring. The ring may form an integral part of the tubular, or may be insertable, removable and replacable between adjacent tubulars. The communication between the electrical conductor and the amplifier-repeater in the ring, may be through conductive contact or by inductive antennae. Preferably, the tubular is a drill pipe having a threaded pin at one end and a threaded box at the other wherein the ring is insertable in the box of one drill pipe section and fixed in position by the pin of an adjacent drill pipe section. Advantageously, the ring comprises a plurality of receiver-amplifiers.

The present invention also provides a ring of the transmission apparatus of the invention. Preferably, the ring comprises at least one amplifier-repeater, a power supply, a receiver antenna, a transmitter antenna. Advantageously, the ring further comprises at least a second amplifier-repeater, a power supply, a receiver antenna, a transmitter antenna. Preferably, the ring comprises at least four such amplifier-repeater, a power supplies, a receiver antennae, a transmitter antennae for each.

The invention also provides a tubular comprising the transmission apparatus of the invention.

The invention also provides a string of the tubulars of the invention, the tubulars connect end to end, wherein the amplifier-repeaters are in series and are powerful enough to drive the signal past at least one following amplifier repeater and on to a third amplifier repeater.

The invention also provides a method for transmitting a signal from deep in a wellbore through a string of tubulars, the method comprising the steps of passing a signal through an electrical conductor arranged in a tubular and amplifying the signal with an amplifier-repeater to enable the signal to travel at a distance substantially equal to between one and ten lengths of the tubular. Preferably, the method further comprises the step of amplifying the signal with the amplifier-repeater to enable the signal to travel at a distance substantially equal to three to five lengths of the tubular. Preferably, such that if an amplifier-repeater fails, the signal can leapfrog over the broken amplifier repeater to the next amplifier-repeater in the next tubular in series with the first. Advantageously, the step of passing the same signal through a second electrical conductor arranged in the tubular and amplifying the signal with a second amplifier-repeater to enable the signal to travel at a distance substantially equal to between one and ten lengths of the tubular. Preferably, the first and second amplifier-repeaters are in parallel and have communication means between them. Advantageously, such that if one amplifier repeaters fails or if one signal conductor fails]

In accordance with the present invention, there is provided a method and apparatus for transmitting data through a drill pipe made up of multiple pieces of drill pipe sections for communication between the surface and a down hole tool in a well bore. The interior of the drill pipe is coated with a thin non-conductive material. The primary use of the present invention is in transferring data between instruments and/or controls located at the bottom and top of multiple lengths of pipe used for drilling wells for oil, gas, or other natural resources. Each length of this drill pipe contains one or more thin conductive wires (for example, 36 gauge wire) or conductive layers of material between the pipe and one or more insulating layers of nonconductive coating. Communication between drill pipe sections of data through these conductive materials between drill pipe sections is performed either by the coupling between drill pipe sections through transmitter-receiver rings, mechanical connections, inductive coupling, or the use of digital repeaters within the collection of pipes. These repeaters can be RF receiver-transmitters coupled either mechanically or through the electromagnetic field produced by these repeaters between the conductive members within the pipes.

In a preferred embodiment, a transmitter receiver ring (T-Ring) amplifier-repeater is provided at each end of a drill pipe section. The T-Ring amplifier repeater picks up signals from one or more wires embedded in an adjacent pipe section above the T-Ring, receives and amplifies the signals, and transmits the signals through wires embedded in the pipe section below the connection.

The preferred embodiment comprises four wires embedded in a protective coating inside the drill pipe. These four wires are brought to the face of each end of the drill pipe section and embedded in a coating and extended on the face as four quadrants of a circle, each section occupying slightly less than 90 degrees, so that the wires are insulated from each other through each drill pipe section. In an alternative embodiment, a micro strip line communication path is provided on the inside of the drill pipe.

A ring-shape Transmission element or "T-Ring" is provided between drill pipe sections. The ring-shaped T-Ring volume can be fitted easily between drill pipe sections. The T-Ring is inexpensive to manufacture and easy to install between existing drill pipe sections fitted with the transmission path of the present invention. The signal received by each T-Ring is amplified and electrically transmitted through the wires in each succeeding drill pipe section to each successive T-Ring. The T-Ring receives the signal, amplifies it, and retransmits it to the adjacent wire through the next pipe. Additional features include detecting failed T-Ring sections and only retransmitting signals associated with functional T-Ring sections. The T-Ring provides its own power from a piezoelectric power generator powered by drilling vibrations and mud flow turbulence through the tool and T-Ring. The T-Ring provides intelligent checksums cyclic redundancy checking and digital packet hand shaking. The dynamic range of each T-Ring is sufficient transmit a signal posting several (e.g. 2-10) drill pipe sections to enable transmitting past failed T-Rings. T-Rings can be active or passive and intermixed

so that only every N (e.g., 5) T-Rings are amplifiers placed in the drill string to boost the signal through passive T-Rings between amplifier T-Rings. T-Rings can also be alternately fired so that amplifying T-Rings take turns amplifying and retransmitting the signal while others rest and store energy to capacitively charge up electric energy to amplify and retransmit when it is their turn.

For a better understanding of the present invention, reference will now be made, by way of example, to the accompanying drawings, in which:

Figure 1 is a schematic illustration of a typical drilling system;

Figure 2 is a schematic illustration of a conductor placed in a tubular under a protective coating in a preferred embodiment of the present invention;

Figure 3 is a view in cross-section taken along line III-III of Figure 2;

Figure 4 is an end view in cross-section of an alternative embodiment of the present invention;

Figure 5 is a side view of a coupling ring located between two drill pipe sections;

Figure 6 is an end view in cross section of the preferred ring showing embedded wires;

Figure 7 is an end view of a preferred embodiment of a T-Ring of the present invention;

Figure 8 is a cross section of the T-Ring shown in Figure 7;

Figure 9 is an end view in cross section of a preferred T-Ring shown with a piezoelectric material coated on the interior surface for power generation;

Figure 10 is a schematic illustration of an alternative embodiment wherein a micro strip line is provided inside of a drill pipe section as a transmission path;

Figure 11 a cross section of a preferred micro strip line provided as a communication path inside of a drill pipe;

Figure 12 is a table illustrating characteristic impedance for a full-section strip transmission line and

line widths; and

Figure 13 is an illustration of a quarter wave impedance matching section.

The present invention enables high speed, real-time data acquisition of formation evaluation data, e.g., resistivity and seismic data. In a preferred embodiment, coatings are applied to the inside of the drill pipe section via several methods. Internal coating must protect the interior of the drill pipe and wires from damage and corrosion in temperatures up to 260°C (500°F).

Sophisticated thermo plastics, such as Halar™ are applied in coating thickness from 0.127mm to 0.76mm (5-30 1000th of an inch (mils)). Pipes can be drill pipe, log pipe or tubing pipes which are thermally pre-cleaned to remove oils and other contaminants that may cause problems with reuse of the abrasive during blasting the inside of the pipe. The blasting also loosens scale inside the drill pipe. The internal surface is then abrasive blasted to take the metal to SAE white metal specification so nothing is left on the internal pipe surface but steel.

Blasting leaves a 0.0127mm to 0.038mm (1/2 - 1 1/2 mil) deep rough pattern on the interior surface of the drill pipe. A phenolic, epoxy or themoplastic primer is then applied to the interior surface 0.05mm (2 mils) thick to account for the 0.038mm (1 1/2) rough pattern and provides a smooth surface on top of the rough surface. Then depending whether a liquid or powered coating is applied, multiple coatings are applied with an intermediate bake cycle between each coating. The bake cycle hardens the applied coating so that an application lance running through the pipe does not score or harm a

previously applied coating layer. Once the desired thickness is reached by the application of multiple layers, a final bake cycle is performed to consolidate all the layers. The intermediate bake cycle is approximately 177°C (350°F) and the final bake cycle 232°C to 246°C (450°F to 475°F).

In powder coating, however, a single coat is applied. Two methods are used to apply the powder coating. One method is to run a lance down the centre of a heated pipe, spraying the powder on the interior of the pipe while the pipe is rotating. The lance is inserted fully into the pipe and drawn along the pipe at a standardized rate to achieve the desired thickness coating the inside of the pipe. Another method is to rotate the pipe, pull a vacuum on the pipe and place a charge of powder into one end of the pipe and purge air behind the charge so that the vacuum pulls the charge of powder along the pipe. The pipe is preferably preheated to facilitate adhesion of powder to the pipe. Still another method of coating the internal wall of the pipe is to place a fibreglass liner in the pipe and epoxy the liner to the interior surface of the drill pipe. Epoxy or grout is used to hold the liner in place. A wire or fibre optic cable can be placed between the interior pipe surface and the liner. Another method of coating is centrifugal casting. A wire is placed on the interior surface of the pipe and a fibreglass cloth placed over the wire and spun to generate 9 g's of force at the interior surface of the pipe. Epoxy is flowed into one end of the pipe. The epoxy is smoothed out and the pipe heated to cure the epoxy.

Each coating method can be used to place a wire or

conductive path on the inside of the pipe beneath the surface of the coating. After the prime step, wires or conductive paths are laid down and coated. Preferably, Teflon coated wires are laid down on the surface of the pipe. Teflon is able to withstand 260°C (500°F), which is above the range of the application of the coating so the Teflon wire survives the coating. 36 gauge wire can be used with as little as 0.5mm (20 mils) of coating and fully cover the wire. The coated wire in the pipe can then be tested under high pressure and high temperature.

The thin coating is important so that the interior diameter of the pipe is not reduced to the extent that it adversely affects the hydrodynamic or pressure carrying properties of the pipe. Initially the thin coating smoothes and improves the hydraulic and hydrodynamic properties of the pipe, however, further restriction or reduction of the drill pipe interior diameter by increasing the layer too much reduces fluid carrying ability of the pipe.

Thicker coatings are also less flexible and reduce the flexibility of the coating. Thus, the thinner coating is used (0.75mm (30 mils) maximum, preferably, 2mm (80 mils) for Halar™ an other thermoplastics in special cases) to make the coating flexible so that it does not crack or break during use downhole.

Below 0.127mm to 1.52mm (5 to 6 mils) coating thickness abrasion resistance may be a problem. For example, mud flow at a velocity that causes turbulent flow, exacerbated by cuttings in the mud, may cause erosion in the coating that may prematurely reduce the life of a coating due to erosion and/or penetration of the coating.

Thus, the coating is preferably between 0.127mm and 0.762mm (5 and 30 mils). Flexibility is extremely desirable in highly deviated well bore. Thus, a 0.762mm (30 mils) coating has been successfully tested in the field with a 36 to 40 gauge wires (approximately equivalent to 0.127mm to 0.0787mm diameter wire) under the 0.762mm (30 mils) coating.

Another consideration is that the thin wire embedded in pipe there is capacitance and inductance between the wire and the pipe metal surface that forms a tuned circuit. The tuned circuit is variable down the length of the pipe. That is, one section of a pipe is tuned at one frequency and another section of the pipe is tuned at a different frequency. Increasing the resistance of the wire by using a smaller wire reduces the height of the peak to obtain a more gradual peak (the Q of the circuit). Thus you reduce the Q by increasing the wire resistance. Thus, this may be an advantage since T-Ring repeaters are provided.

In an alternative embodiment (Figure 4), a first insulating layer is applied to the interior of the drill pipe, then a conductive second coating and an insulating top coat. This forms a layer of conductive coating. A single breach in the insulating layer may cause the conductive mud to short out the conductive layer. The coating protects the conductive wires from turbulent mud flow abrasion.

In another embodiment the conductive layer can be divided into longitudinal strips so that the entirety of the conductive paths are not shorted by a breach at a single point in the insulating layer adjacent the mud.

Multiple wires also serve to provide multiple conductive paths that are not subject to a single point of failure.

In an alternative embodiment, electrical signals are converted to an acoustic signal that travels down the interior of the pipe or the body of the pipe. Travelling down the body of the pipe of each drill pipe section and bridging the juncture of drill pipe section with an acoustic to electric conversion to overcome the difference of acoustic impedance at the drill pipe connections between sections.

The inside of the T-Ring is exposed to turbulent mud flow which provides pressure variations on the piezoelectric device formed on the interior surface of the T-Ring adjacent the mud flow to generate power to the T-Ring. Drilling vibrations can also be used to generate power via the piezoelectric device. The processor in each of the four receiver sections, in each T-Ring preferably performs a check sum. The check sums are compared and only the received signals with a matching check sum are retransmitted by the T-Ring. In another embodiment the T-Ring provides processor with memory provide a store and forward digital packet communication scheme wherein a digital packet is received and stored until a signal is received from another device or T-Ring to retransmit the packet. Preferably each T-Ring and each individual T-Ring section has a unique digital address so that a T-Ring or T-Ring section can be reprogrammed, commanded or shut down by commands directed to the address via the communication path. Specific transmission and operations modes for the T-Rings can be commanded by commands sent to the T-Rings and T-Ring segments via the communication path. A lithographic

technique can be used to form the antennae in the T-Rings.

Figure 1 illustrates a schematic diagram of a MWD (Measurement Whilst Drilling) system 10 with a drill string 20 carrying a drilling assembly 90 (also referred to as the Bottom Hole Assembly, or "BHA") conveyed in a "well bore" or "borehole" 26 for drilling the well bore. The drilling system 10 includes a conventional derrick 11 erected on a floor 12 which supports a rotary table 14 that is rotated by a prime mover such as an electric motor (not shown) at a desired rotational speed. The drill string 20 includes tubing such as a drill pipe 22 extending downward from the surface into the borehole 26. The drill bit 50 attached to the end of the drill string breaks up the geological formations when it is rotated to drill the borehole 26. If a drill pipe 22 is used, the drill string 20 is coupled to a draw works 30 via a Kelly joint 21, swivel 28 and line 29 through a pulley 23. During drilling operations, the draw works 30 is operated to control the weight on the drill bit 50, which is an important parameter that affects the rate of penetration. The operation of the draw works is well known in the art and is thus not described in detail herein.

During drilling operations, a suitable drilling fluid 31 from a mud pit (source) 32 is circulated under pressure through a channel in the drill string 20 by a mud pump 34. The drilling fluid passes from the mud pump 34 into the drill string 20 via a desurger 36, fluid line 38 and Kelly joint 21. The drilling fluid 31 is discharged through an opening in the drill bit 50 at the bottom of the borehole. The drilling fluid 31 circulates up hole through the annular space 27 between the drill

string 20 and the borehole 26 and returns to the mud pit 32 via a return line 35. The drilling fluid acts to lubricate the drill bit 50 and to carry borehole cutting or chips away from the drill bit 50. A sensor S1 preferably placed in the line 38 provides information about the fluid flow rate. A surface torque sensor S2 and a sensor S3 associated with the drill string 20 respectively provide information about the torque and rotational speed of the drill string. Additionally, a sensor (not shown) associated with line 29 is used to provide the hook load of the drill string 20.

In a preferred embodiment of the invention, a downhole motor 55 (mud motor) is disposed in the drilling assembly 90 to rotate the drill bit 50 and the drill pipe 22 is rotated usually to supplement the rotational power, if required, and to effect changes in the drilling direction.

In the preferred embodiment of Figure 1, the mud motor 55 is coupled to the drill bit 50 via a drive shaft (not shown) disposed in a bearing assembly 57. The mud motor rotates the drill bit 50 when the drilling fluid 31 passes through the mud motor 55 under pressure. The bearing assembly 57 supports the radial and axial forces of the drill bit. A stabilizer 58 coupled to the bearing assembly 57 acts as a centralizer for the lowermost portion of the mud motor assembly.

A drilling sensor module 59 is placed near the drill bit 50. The drilling sensor module 59 contains sensors, circuitry and processing software and algorithms relating to the dynamic drilling parameters. Such parameters preferably include bit bounce, stick-slip of the drilling assembly, backward rotation, torque, shocks, borehole and

annulus pressure, acceleration measurements and other measurements of the drill bit condition. A suitable communication sub 72 sends data to the surface and receives data from the surface a communication path conductive path provided by the present invention. The drilling sensor module 59 processes the sensor information and transmits it to the surface control unit 40 via the communication path provided by the present invention.

The communication sub 72, a power unit 78 and an Nuclear Magnetic Resonance (NMR) tool 79 are all connected in tandem with the drill string 20. Flex subs, for example, are used in connecting the NMR tool 79 in the drilling assembly 90. Such subs and tools form the bottom hole drilling assembly (BHA) 90 between the drill string 20 and the drill bit 50. The drilling assembly 90 makes various measurements including the pulsed nuclear magnetic resonance measurements while the borehole 26 is being drilled. The communication sub 72 obtains the signals and measurements and transfers the signals via the communication path provided by the present invention to the surface to be processed. Alternatively, the signals can be processed using a downhole processor in the drilling assembly 90. The BHA 90 may be on the bottom end of a drill string, which may be from 100m to 20,000m or more in length.

The surface control unit or processor 40 also receives signals from other downhole sensors and devices and signals from sensors S1-S3 and other sensors used in the system 10 and processes such signals according to programmed instructions provided to the surface control unit 40. The surface control unit 40 displays desired

drilling parameters and other information on a display/monitor 42 utilized by an operator to control the drilling operations. The surface control unit 40 preferably includes a computer or a microprocessor-based processing system, memory for storing programs or models and data, a recorder for recording data, and other peripherals. The control unit 40 is preferably adapted to activate alarms 44 when certain unsafe or undesirable operating conditions occur.

Turning now to Figure 2 a schematic illustration of a tubular with one or more conductive wires 204 preferably paths, comprising 36 gauge wire or conductive strips are provided. Preferably, the conductive strips have an equivalent cross sectional conductive area to 36 gauge wire. The conductive wires 204 are insulated from the interior surface 210 of the wall 202 of the tubular by the use of non-conductive material coating 208 bonded to the pipe, preferably by the application of one or more thin layers of non-conductive materials. Data is transferred along a communication path between the tubular 200 via the conductive path or conduit 204. The communication path, preferably wire(s) 204 is then coated by thin protective and/or insulating layer 206 to protect communication path 204 from abrasion. The layers are preferably approximately 0.05mm to 1mm (2 to 40 mils) thick. Thicker wires and layers can be utilized, however, the thin wires and coating layers are preferred for enhanced drill pipe flexibility during drilling operations. A coating thinner than 0.127mm (5 mils), preferably 5 millimetres is too thin to protect against abrasion properly. The tubular shown may take the form of a drill pipe, which additionally comprises a box at one

end and a pin thread at the other.. It should be noted that the relative dimensions of the wall of the tubular, the wires 204, the insulative coating 208 and the protective coating 206 are not to scale and are simply for illustrative purposes only.

Turning now to Figure 3, a cross-section of the wire provided in Figure 2 is illustrated taken along line III-III. As shown in Figure 3, communication path 204 lies between interior surface 210 of the wall 202 of the tubular 200 and the interior surface 211 of coating 206. The coating 206 may have a thickness which reaches the top of the wire, as indicated by the dashed line, or may cover the wire completely and may advantageously provide a thickness above the top of the wire for protecting the wire. An additional coating may be applied to the interior surface 210 to insulate communication path 204 from the interior surface 210 of tubular 200.

Turning now to Figure 4, in an alternative embodiment, a method and apparatus according to the present invention comprises the use of one or more layers 260 of a non-conductive material applied to coat the interior surface 210 of a tubular 200, such as a section of drill pipe. The application of the non-conductive material is followed by the application of one or more layers of conductive material 250 and the further application of non-conductive materials over the conductive material 240. The conductive material 250 forms a communication path for data from one end of a drill pipe section to the other. This alternation of application of conductive and nonconductive layers can be repeated allowing multiple separate conductive layers and communication. These layers of conductive material are

then connected through a T-Ring described below or by mechanical means, induction, or shared electromagnetic fields from one section of drill pipe to another section of drill pipe allowing the transfer of data between multiple joints of the preferred drill pipe. In an alternative embodiment, the present invention comprises repeaters 212 located at points within the communication path or conduit. These repeaters can be located between the internal upset on the back end of the box connection of the drill pipe and the end of the pin connection made up into it. It is also possible to temperature stabilize the electronics by boiling a coolant into the pipe ID at the high pressures normally encountered. The repeaters or T-Rings can be powered by piezoelectric, magneto hydrodynamic or other methods or generating power down hole. A battery may also be used to provide power.

The advantages provided by the addition of a layer of non-conductive material over the conductive materials include the protection of the conductive materials from abrasion damage and the intrusion of partially conductive materials as well as the reduced pressure loss allowed by the location of the conductive materials on the pipe surface. The addition of the internal coating preferably also provides improved hydrodynamics for flow within the drill pipe. The communication path coating is preferably non-conductive to insulate the conductive communication path from the interior of the drill pipe section, or from other conductive paths formed inside the drill pipe section.

Each section of drill pipe is preferably abrasive blasted and coated with a plastic (or other non conductive) coating having a high resistivity as known in

the state of the art. This drill pipe section is then tested to insure that the high resistance coating is not breached by metal shavings, or pinholes in the coating. After this testing is completed a conductive material is applied. This can be a metal filled plastic coating, a thin layer of conductive foil treated to adhere to the plastic coating, or one or more wire conductors treated to adhere to the coating. This conductive layer is then covered by one or more additional layers of non-conductive coating. This drill pipe section is again tested to insure that the conductive layer is intact and that it has a high resistance to the pipe body or to a conductive fluid held within the pipe. The conductive layer is then connected to either an electrical connector, or to an inductive coupling ring, or to an electronic repeater. The system is then further sealed by a non-conductive coating and tested.

Once multiple drill pipe sections have been prepared the drill pipe sections are connected to form a drill string having a communication path. The communication path enables data to be transmitted through the conductive layer from one end of the connected drill pipe section to the other end. The conductive path may also be formed as conductive longitudinal strips rather than a continuous layer.

There are many methods of installing a suitable wire for the present invention. These include centrifugal casting of a coating, preferably plastic over the wire, preheating the pipe and depositing the coating using a vacuum system, or applying the coating by flocking the coating over the wire or conductive path.

These techniques perform well in harsh environmental

conditions associated with down hole drill pipe service. In another embodiment, the apparatus and method comprises using Teflon coated wire pairs. These Teflon coated wire pairs are applied over a non-conductive primer coat giving dual insulation. The finish coat is applied over the wire. On a section through the wire one would find the substrate, a thin phenolic primer, teflon, copper, teflon, and the finish coat of epoxy-phenolic.

Turning now to Figures 5 and 6, a preferred embodiment of a communication coupling ring (T-Ring) is illustrated. A major difficulty in communication through wire inside drill pipe is the connection problem between drill pipe sections. In a passive system without an amplifier-repeater between drill pipe sections, the coefficient of coupling between sections would have to be at least 99% on each of the 700 connections possible on a deep well string to enable communications through the drill string within the dynamic range of present electronics.

An electronic device, such as a sensor/transducer produces an electrical signal which is generally amplified and transmitted through a wire to a processing unit such as a computer. Due to line losses in the wire, the signal can only travel a specified distance through a wire. An amplifier-repeater is inserted at a point equal or less than the recommended distance along the wire that the signal can be sent. The amplifier-repeater boosts the signal at those points so that the signal can travel through the following section of wire. A problem with known amplifier-repeaters is that they require a source of power and are often the weak point in reliability. The environment in the drill string may include pressures

above 700 bar (10,000 psi) absolute pressures and temperatures above 200 degrees Centigrade with possible excursions up to 250 degrees Centigrade.

Thus, in a preferred embodiment, a T-Ring amplifier-repeater is preferably provided at each drill pipe connection between drill pipe sections. The T-Ring amplifier repeaters pick up signals from the conductive path, e.g., one or more conductive paths, wires or strips are embedded in a drill pipe section above the T-Ring, amplifies the signals, and transmits the signals through wires or conductive paths embedded in the pipe below the T-Ring connection. A preferred embodiment comprises four wires embedded in a protective coating inside the drill pipe. These four wires are brought to the face of the drill pipe connection on each end of a drill pipe section and embedded in the coating as four sections or quadrants of a circle, each section occupying slightly less than 90 degrees, so that the wires are insulated from each other through each drill pipe section. The connection between the drill pipe is provided by a T-Ring with a ring-shaped volume which is fitted with the transmitter/receiver amplifier-repeater. The signal is electrically transmitted through the conductive path, e.g., wire in a drill pipe section to each T-Ring. The T-Ring receives the signal from the wire in the drill pipe, amplifies the signal, and transmits the amplified signal to the adjacent wire through the next drill pipe section.

The T-Ring comprises of (one or more of each) a power source, preferably utilizing mechanical energy available from the drill pipe to create electrical power, a receiver that senses the signal from the wire in the transmitting pipe, an amplifier to increase the signal

power, and a transmitter which couples the amplified signal to wire in the next pipe. This unit is totally sealed and easily replaceable while the drill pipe sections are being connected. The electronics in the T-Ring preferably provide signal conditioning devices, dedicated logic circuits for fault detection, and self-repair by eliminating the signal conduits which are damaged. The T-Ring provides sufficient dynamic range so that the complete failure of one or more T-Ring amplifier-repeaters can be tolerated by amplification of surrounding rings that enable a T-Ring to transmit past a failed T-Ring to the next drill pipe section or T-Ring. In an alternative embodiment, the T-Rings simply receive and retransmit between each other without the benefit of a conductive path in the drill pipe section between the T-Rings.

In an alternative embodiment the drill pipe wires terminate in a passive antenna at both ends of the drill section pipe and the T-Ring amplifier-repeater acts as an active receiver and transmitter without any connection between the drill pipe wires and the ring. Thus the ring is a drop in part that fits loosely between the gap between the bottom of the pin and the bore of the box much like corrosion rings inserted in drill strings today.

Turning now to Figure 5, a preferred T-Ring 300 is shown installed between two adjacent drill pipe sections 200. As shown in Figure 5, T-Ring 300 drops in between drill pipe sections 200 during connection and assembly of a series of drill pipe sections to form a drill string.

Turning now to Figure 6, the drill pipe end 302 of a drill pipe section 200 is illustrated showing four

conductive paths 308, 310, 312, and 314, terminating at the drill pipe end 302 of drill pipe section 200. Each conductive path is extended in a quadrant of approximately 85 degrees forming an arc along the circular cross section 302 of the drill pipe section end. Conductive paths 308, 310, 312, and 314 are extended along the drill pipe section end face 302 in arcs 309, 311, 313, and 315 respectively. The centre 318 of the drill pipe section is hollow to allow flow through the drill pipe. The conductive path arcs 309, 311, 313 and 315 are covered with a coating or washer to insulate and/or protect the conductive path arcs 309, 311, 313 and 315 forming the communication path end. The arcs are separated by a space 301 to prevent the conductive paths from touching.

Turning now to Figure 7, a cross section of a preferred T-Ring 400 is shown. The face of T-Ring 400 comprises four T-ring segments 409, 411, 413, and 415 receiver-transmitter antennae of the cylindrical T-Ring 400.

As shown in Figure 7, each T-Ring has a power supply 420 and an amplifier 422. The power supply 420 can be a heat resistant battery, either long life or disposable or rechargeable or a power generating device such as a piezoelectric element that generates electric power from the mechanical vibration of drilling or turbulent flow and pressure fluctuations of mud flow through centre opening 418 of T-Ring 400. A mud motor may also generate power transferred to the T-Rings via inductive coupling or through the conductive paths. In this case, the data signal is super imposed over the power on the data path 308, 310, 312, or 314. Amplifier 422 contains signal

conditioning circuitry and a processor to perform cyclic redundancy checking, fault detection and digital packet reception and retransmission.

In a preferred embodiment the T-Rings take turns storing power for operation and alternately receiving and retransmitting data signals. Preferably a T-Ring has sufficient dynamic range to transmit past a failed T-Ring. Thus in a series of five consecutive T-Rings only one of five rings need be active at one time to receive and transmit while the other four T-Rings are storing power in e.g. a capacitor. Each T-Ring takes 1 of 5 turns receiving and transmitting. If one of the five T-Rings fails it is skipped over by adjacent T-Rings. For example if T-Ring 3 fails T-Ring 2 would communicate with T-Ring 4 instead of the normal T-Ring 2 to 3 and T-Ring 3 to 4 T-Ring communication.

Figure 8 is a cross section AA of Figure 7. As shown in Figure 8, T-ring segment 409 comprises a receiver antenna (not referenced) located on face 401 and a transmitter antenna (not shown) located on face 402. T-ring segment 411 comprises a receiver antenna (not referenced) located on face 401 and a transmitter antenna (not shown) located on face 402. T-ring segment 413 comprises a receiver antenna 413a located on face 401 and a transmitter antenna 413b located on face 402. T-ring segment 415 comprises a receiver antenna 415a located on face 401 and a transmitter antenna 415b located on face 402. The receiving and transmitter antennae are covered with a protective coating 421. The receiver antennae are located on T-Ring face 401 and each receives signals from an antenna 309, 311, 313 and 315 on the end 302 of an adjacent drill pipe section 200. The signal received by

receiver antenna is amplified by its own amplifier 420 powered by its own power supplies 422 and retransmitted by the transmitter antenna to antennae in the pin of a connected drill pipe.

Processor/Amplifiers 420 are interconnected by data path 423 for status and reporting between the four T-Ring segments 409; 411; 413; and 415. Figure 9 is a cross section of a preferred T-Ring shown with a piezoelectric material coated on the interior surface for power generation.

Thus each T-Ring comprises four sections 409; 411; 413; and 415 each comprising receiver and transmitter antennas, power supplies 422 and process/amplifiers 420. The processor can detect when a section 409, 411, 413, or 415 has failed and will retransmit only the sections that are functional. Thus if T-ring section 409 fails, only signals received by sections 411, 413 and 415 will be retransmitted.

If wire 309 is damaged and unable to carry a signal along the length of the drill pipe, the other three 311, 313 and 315 of the four wires will be able to carry the signal and received by receiver antennae 411a, 413a and 415a. The signal will then be passed between all four processor units 420 and transmitted through all four transmitter antennae 409b, 411b, 413b and 415b and received by all four wires (conductors) in the pin end of the adjacent drill pipe. In the same way, two or three wires may fail in each drill pipe section whilst still maintaining data integrity through the entire drill string.

A transmission line using number 26 enameled wire, 0.4mm (0.0159″) diameter copper, enamel coated (standard

magnet wire) can be utilized for the transmission path. The wires are preferably placed a few mils apart, side-by-side, to act as an RF line. The wires can be coated into position very loosely twisted the wires together or laid out side-by-side. In a test, at 730 MHz the loss in a 3.15m (10′ 4″) section is about 6 dB for this configuration of the communication path. The wires were tested in a balanced configuration, driven and loaded by a 50Ω coaxial system. In the test no baluns or any form of matching was used. The wire ends were soldered to some SMA coax connectors. The VSWR in a 50Ω system and the transmission losses were measured. Squeezing and manipulating the wire pair at various points where there might have been gaps resulted in a return loss of about 20dB at which time the transmission loss was minimized and was about 6 dB for the section. The same length of RG-174 was measured at 3.1 to 3.2dB loss at 730 MHz using the same connectors. Building RF transmission lines with parallel ribbon conductors, which could be wider than the #26 wires, form an assembly thin enough to fit desired maximum overall thickness of less than 1mm (40 mils) for the coating inside of a drill pipe section.

Figure 10 is a schematic illustration of an alternative embodiment wherein a micro strip line is provided inside of a drill pipe section as a transmission path. Figure 11 is a cross section of a preferred micro strip line provided as a communication path inside of a drill pipe. Figure 12 is a table illustrating characteristic impedance for a full-section strip transmission line and line widths. Figure 13 is an illustration of a quarter wave impedance matching section. Turning now to Figure 10, a preferred micro

strip line communication path is illustrated. Alternatively dielectric-supported strip lines such as parallel ribbon conductors, can be used, thereby maximizing the conductor widths while keeping within the desired overall thickness limitations of the approximately 0.635mm (0.025") coating thickness. Figure 10 illustrates a thin, full-section micro strip line transmission line or communication path inside of a drill pipe section to maintain 50Ω impedance levels with convenient line widths. A thin, full-section micro strip line as shown in Figure 10 works well. As shown in Figure 10, er is ϵr, the relative dielectric constant, of the material inside of the full-section strip line transmission line assembly. The edges of the assembly are preferably rounded as shown in the Figure 11 diagram below, as long as the width of the ground plane portions is 3 or 4 times the width of the centre conductor, w. Preferably, the centre conductor width is maximized in order to minimize losses, since the centre conduct is where most of the losses manifest. The wider the centre conductor, the lower the losses in the centre conductor. The characteristic impedance, Z_0, of the micro strip line transmission path shown in Figure 10 and 11 decreases with increasing width, however, so there is a compromising process.

Preferably, a foil package is fabricated with a center conductor suspended in a material with a dielectric constant, with ϵr, as low as possible having a low loss tangent. TFE or Teflon is a suitable material, with an ϵr of 2.1 and dissipation factor between 0.0003 and 0.0004, although Teflon filled with hollow silica micro-spheres or a similar material is preferred, with an

Єr of 1.2 and substantially the same dissipation factor. The table shown in Figure 12 shows some representative characteristic impedance values for Teflon in various center conductor widths "w" 1010 and thickness "t" 1012 and material thickness "b" 1014 and coating thickness 1002.

In the full-section strip line, RF current flows on both sides of the center strip 1108 so the area to support current is comparable to a coaxial line with a round center conductor of a diameter substantially less than the width w. The predicted losses for the micro strip lines shown in Figure 10 and 11 above using TFE dielectric are less than for miniature coaxial lines. It is expected that less than the 8 dB per 9.1m (30 feet) will be typical for a preferred embodiment. The preferred full-section strip line transmission lines should be more efficient than the RG-174 coaxial cable. The circumference of the # 26 centre conductor in the RG-174 coax is about 0.127mm (0.050") whereas the effective width of the 25 ohm line below (third up from the bottom) is 1.3mm (0.051") and the solid, smooth ground planes should be slightly better than the single-thickness braid used on the coax outside conductor. Also, the dielectric material in the strip line is preferably better than the polyethylene used in the coax.

As shown in Figure 12, W/b and Z_0 data is from the Microwave Engineers' Handbook, Vol 1, Artech House. The last column in the chart is the total thickness of the coatings and the transmission line assembly.

As shown in Figure 13, allowing the impedance, Z_0 of the strip line 1000 to go down to 25 ohms allows the center conductor to become wider to exhibit lower losses.

A quarter wavelength (about 10cm) impedance matching section 1302, as shown below in Figure 13, matches (step-up) the line to the effective impedance (resistance at resonance) of the coupling loops 1304 at the passive ends of the pipe length. The amplifier assembly is used for matching to the intermediate loops. In this way, most of the line length (9m (29 feet)) can be lower loss.

As shown in Figure 12, a preferred embodiment comprises strips of 0.05mm (0.002″) copper foil about 0.635mm (0.025″) wide. Standard 1 oz. Cu PCB foil is 0.0356 (0.0014″) thick and 2 oz. Cu clad is 0.0711mm (0.0028″) thick. Skin depth is about 0.006mm (¼ mil) enabling use of 1 oz. Cu stock. The Cu stock is preferably glued to a strip of Teflon and a line fabricated. Since we can measure the impedance characteristics accurately with the UNR network analyzer, we can separate matching losses from I^2R losses. Therefore, a 3.05m (10 feet) length should be enough to determine possibilities.

The dielectric material 1116 in the transmission line holds the centre conductor strip in place between the ground planes and preferably, the dielectric material does not have to uniformly surround the centre strip 1118. All dimensions are non-critical, with 10% tolerances. Once the preferred embodiment is manufactured it can be characterized and used however it comes out. The preferred communication path assembly then stays relatively constant. The dielectric preferably comprises two separate strips of Teflon-like material, one below the center strip 1118 and one above 1114, and the whole positioned in between the outer conductors 1104 and 1106.

The outer conductors 1104 and 1106, or ground planes

are preferably one piece of copper foil, wrapped around the insides, folded and crimped, or cold-welded, on the open side to form a surrounding structure enveloping the dielectric material 1116 and centre conductor 1108. Alternatively, one of the dielectric strips could be extruded with a 0.05mm x 0.0635mm (0.002" x 0.025") channel extruded into it to hold the centre strip. Alternatively, the dielectric strip can be run through a machine to cut a grove along its length. There numerous manufacturing techniques to fabricate the preferred communication path assembly.

The invention provides a drill pipe communication path comprising: a drill pipe section having a conducting member located adjacent an interior surface of the drill pipe; and a coupling for connecting a plurality of the drill pipe sections so that data can be transferred from one end of the drill pipe section to the next. Preferably, the apparatus further comprises a thin coating for covering the conducting member. Advantageously, the conducting member further comprises a micro strip line. Preferably, the coupling comprises a repeater-amplifier. Advantageously, an inductive coupling, an acoustic coupling, or a digital repeater may be used.

The invention also provides a method for manufacturing a drill pipe communication path comprising: positioning a conductive member adjacent an interior surface of a drill pipe section; and connecting a plurality of drill pipe sections so that data can be transferred along the communication path from one end of the drill pipe section to the next. Preferably, the method further comprises covering the conductive member

with a thin coating. Advantageously, the method further comprises depositing a micro strip line inside of the drill pipe.

While the foregoing disclosure is directed to the preferred embodiments of the invention various modifications will be apparent to those skilled in the art. It is intended that all variations within the scope and spirit of the appended claims be embraced by the foregoing disclosure. Examples of the more important features of the invention have been summarized rather broadly in order that the detailed description thereof that follows may be better understood, and in order that the contributions to the art may be appreciated. There are, of course, additional features of the invention that will be described hereinafter and which will form the subject of the claims appended hereto.